ブラックホール周りのアクシオン雲からの電磁放射

(Electromagnetic radiation from axion cloud around Kerr BHs)

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Outline

1. Introduction
2. What we want to do
3. Our work
   - Initial data
   - Flat space analysis
   - Around Kerr BH
   - Supper-radiance effect
4. Summary

Scalar field

- Scalar field is the simplest field in field theory.
- Scalar field often appears.
  - pion, Higgs
  - Strong CP problem $\Rightarrow$ QCD axion
  - String axion
  - Dark Matter / Energy
  - Modified gravity et al
- Plausible iteration with photon

cf: $F_{\mu\nu} = \nabla_\mu A_\nu - \nabla_\nu A_\mu$

  - axion type interaction $\Leftarrow$

$$\mathscr{L}_{\mathrm{a}} = -\frac{k_{\mathrm{a}}}{2}\Phi * F^{\mu\nu}F_{\mu\nu} = -2k_{\mathrm{a}}\Phi \vec{B}\cdot\vec{E}$$

  - scalar type interaction

$$\mathscr{L}_{\mathrm{s}} = -\frac{\left(k_{\mathrm{s}}\Phi\right)^p}{4}F^{\mu\nu}F_{\mu\nu} = -\frac{\left(k_{\mathrm{s}}\Phi\right)^p}{2}\left(\vec{B}^2 - \vec{E}^2\right)$$

Scalar field around Kerr BH

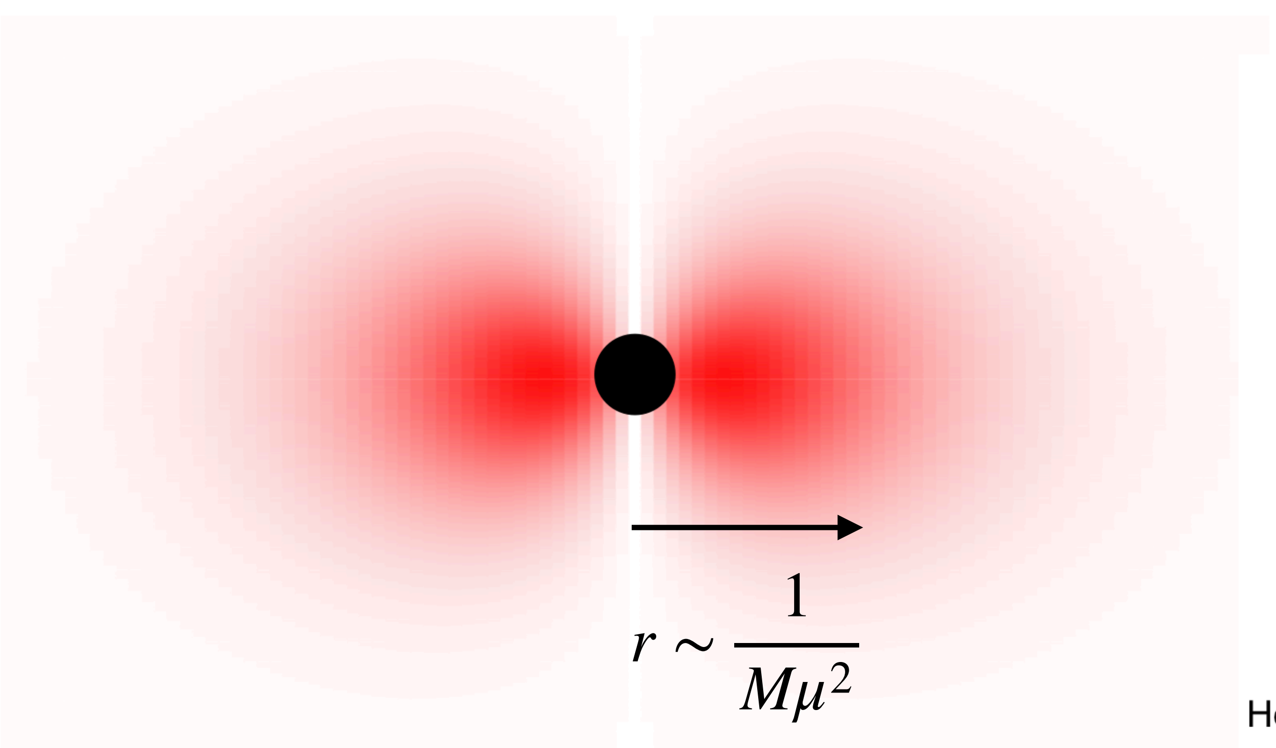
- Super-radiance
  - Relevant mass range : $10^{-22}\mathrm{eV} < \mu < 10^{-10}\mathrm{eV}$
  - condition : $\omega < m\Omega_\mathrm{H}$

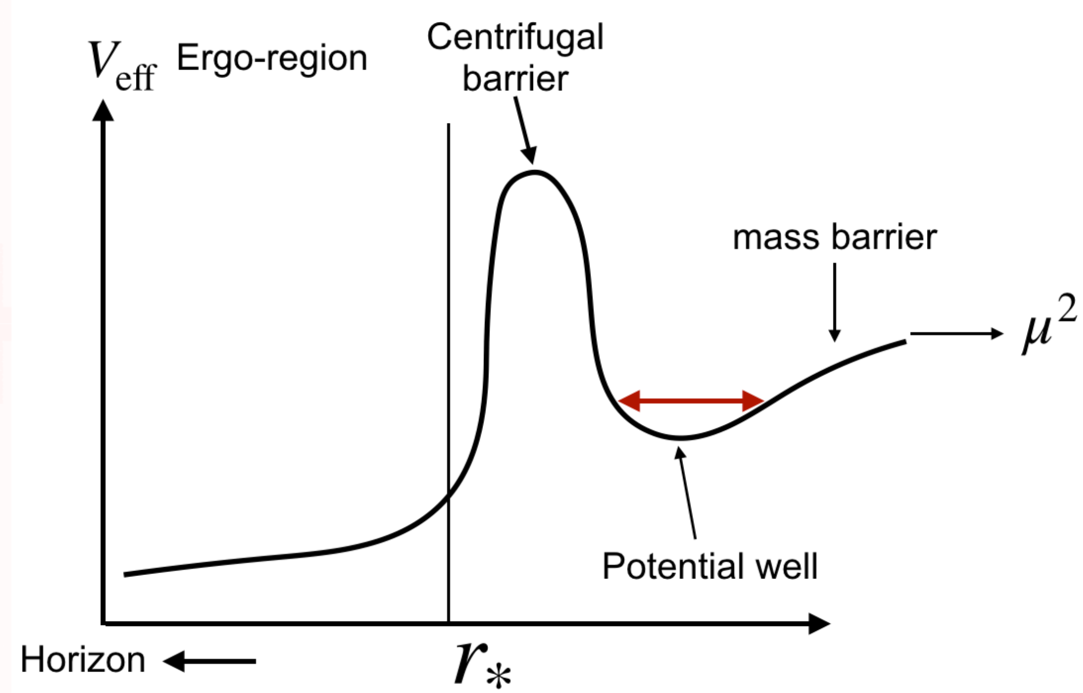
Ω_H : angular velocity

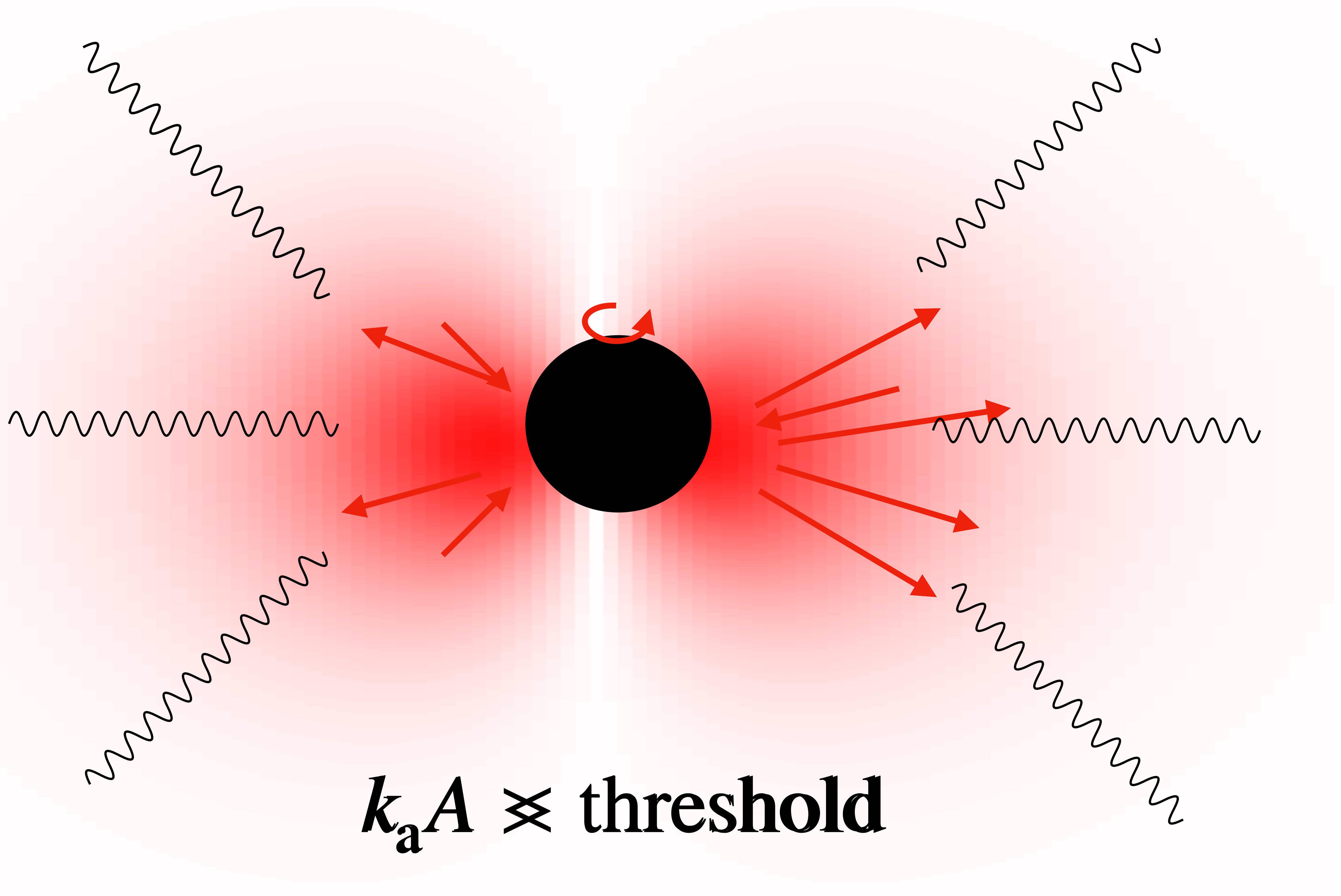
$\Phi(x) = e^{-i\omega t} e^{im\phi} S_{lm}(\theta) R_{lm}(r)$

- Scalar field can be localized as cloud around BH

$$r_\mathrm{cloud} \sim \frac{(l+n+1)^2}{(M\mu)^2} M$$






$k_a A \gtrless$ threshold

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What we want to do

- Previous work
  - Spatially uniform coherent oscillating axion field (Sen, 2018)

$$\nabla_\mu F^{\mu\nu} = 2k_a \tilde{F}_{\nu\mu} \nabla^\mu \underline{\Phi} \longleftarrow \Phi = \Phi_0 e^{-i\mu t} + \Phi_0^* e^{i\mu t}$$

$\Rightarrow$ Exponential growth of EM field

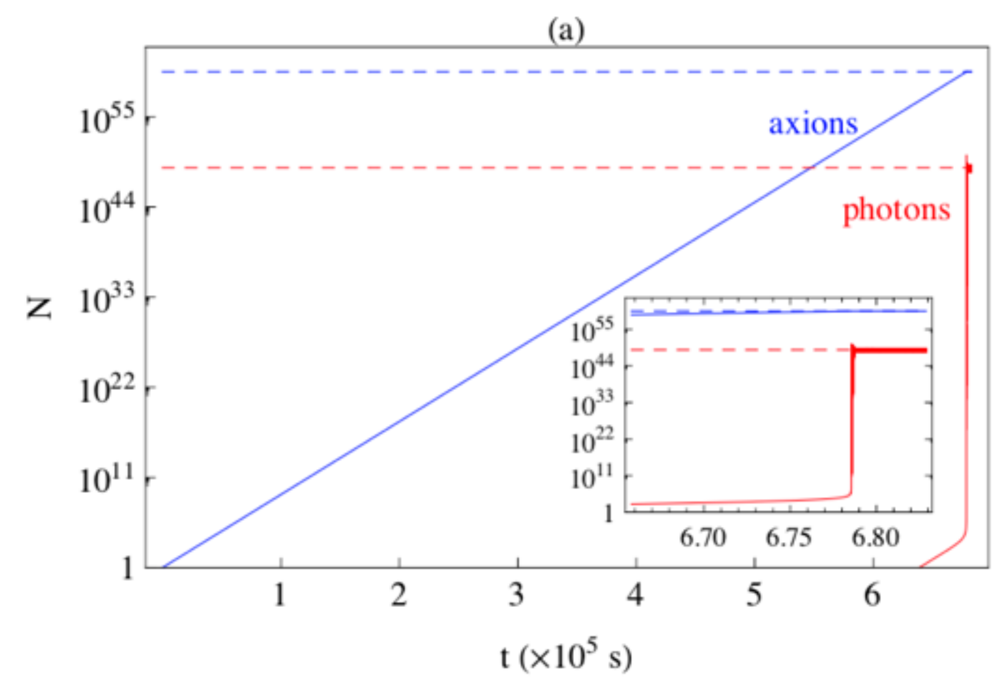
  - The laser like emission of EM field from axion cloud is predicted by solving Boltzmann eq. (J.G.Rosa et al 2018)

N_ϕ : number of axions for 2p state

N_γ : number of photons for 2p state

Γ_ϕ : spontenious axion decay width

$$\begin{cases} dN_\phi/dt = \Gamma_s N_\phi - \Gamma_\phi \left(N_\phi(1+AN_\gamma) - B_1 N_\gamma^2\right) \\ dN_\gamma/dt = -\Gamma_e N_\gamma + 2\Gamma_\phi \left(N_\phi(1+AN_\gamma) - BN_\gamma^2\right) \end{cases}$$



What we want to do

- What we want to do is
  - solving Klein-Gordon equation and Maxwell equation with interaction around Kerr background.

$$\begin{cases} (\nabla^2 - \mu^2)\Phi = \dfrac{k_{\mathrm{a}}}{2}\tilde{F}_{\mu\nu}F^{\mu\nu} \\ \nabla_\mu F^{\mu\nu} = 2k_{\mathrm{a}}\tilde{F}_{\nu\mu}\nabla^\mu\Phi \end{cases}$$

- What we did
  - 3+1 decomposition (with constraint damping scheme)
    - Evolution equation
    - Gauss law (constraint equation)
  - use Kerr-schild form metric.
  - develop c++ code for time evolution

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Initial data

- Scalar field : axion cloud

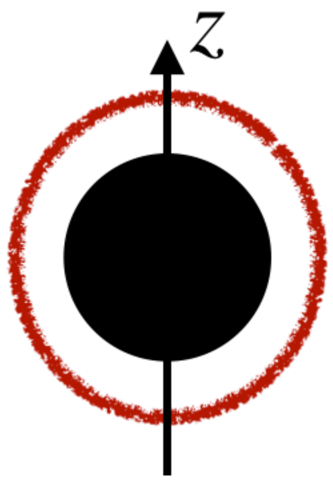
$$\Phi = A_0 g(\tilde{r}) \cos(\varphi - \mu t) \sin\theta$$

$k_a A_0$: effective coupling for EM field

$$\begin{cases} g(\tilde{r}) = \tilde{r} e^{-\tilde{r}/2} \\ \tilde{r} = r M \mu^2 \end{cases}$$

- EM field
  - 1. extended profile

$$E^\varphi = E_0 e^{-(\frac{r-r_0}{w})^2} \quad E^r = E^\theta = B^i = 0$$



  - 2. localized profile

$$E^\varphi = E_0 e^{-(\frac{r-r_0}{w})^2} \Theta(\theta) \qquad E^r = E^\theta = B^i = 0$$

$$\Theta(\theta) = \begin{cases} \sin^4(4\theta) & (0 \leq \theta < \frac{\pi}{4}) \\ 0 & (\frac{\pi}{4} \leq \theta < \pi) \end{cases}$$

initial parameter : E_0, r_0, w
(These profile satisfy Gauss's law.)

  - The result qualitatively does not change.

Instability in flat space

$$(FF)_{00} = \int d\Omega F^{\mu\nu} F_{\nu\nu} Y_{00}$$

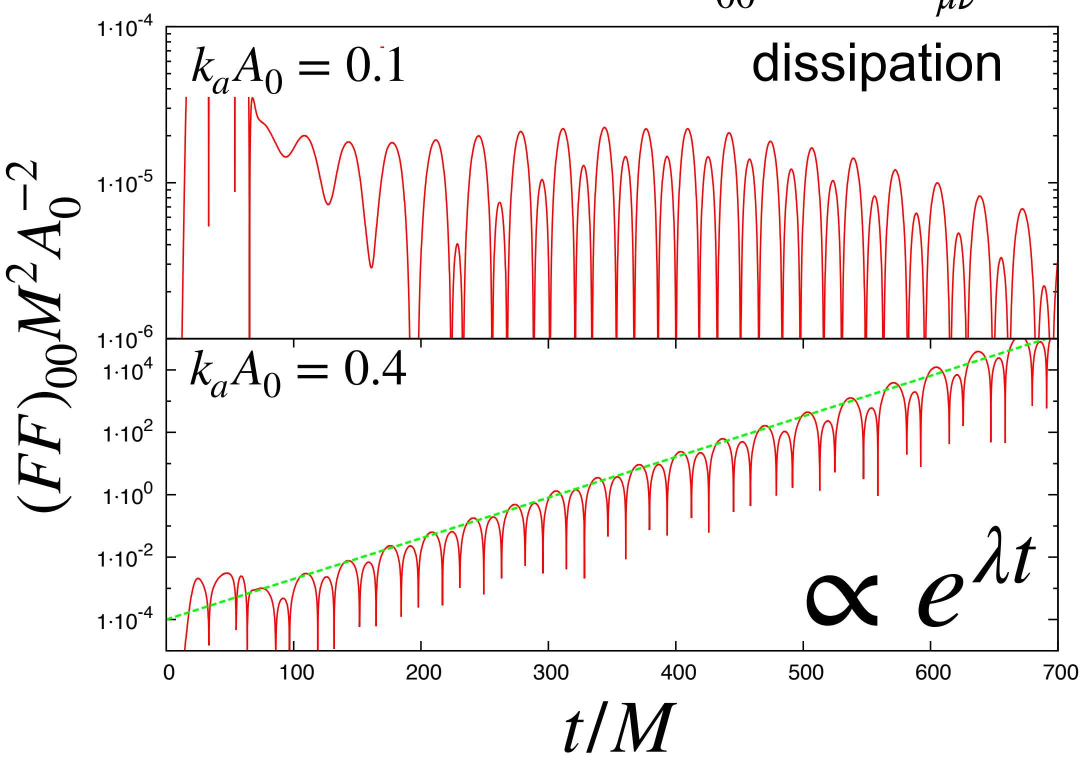
- EM field under the fixed axion cloud in flat space.

$$\nabla_\mu F^{\mu\nu} = 2k_{\mathrm{a}} \tilde{F}_{\nu\mu} \nabla^\mu \Phi$$

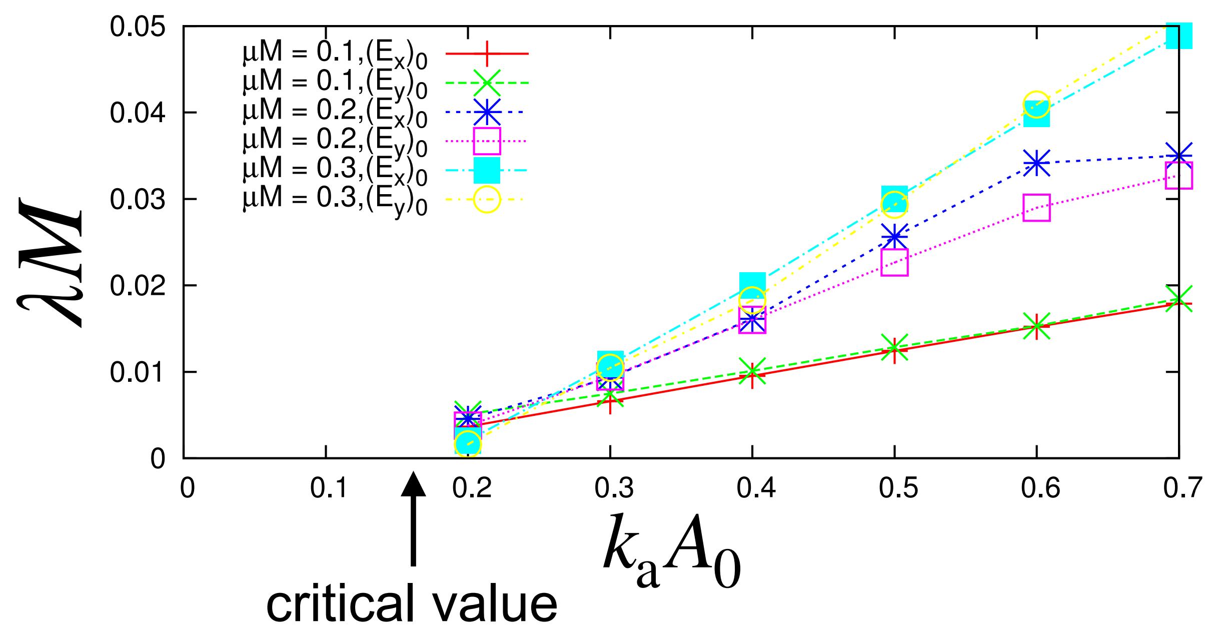
axion cloud : $\Phi = A_0 g(\tilde{r}) \cos(\varphi - \mu t) \sin\theta$

  - When the coupling is larger than a certain value, the EM field grows exponentially.

Time evolution of Y_{00} of $F^{\mu\nu}F_{\mu\nu}$



Relation between λM and $k_{\mathrm{a}} A_0$ for each mass μM



Around Kerr BH

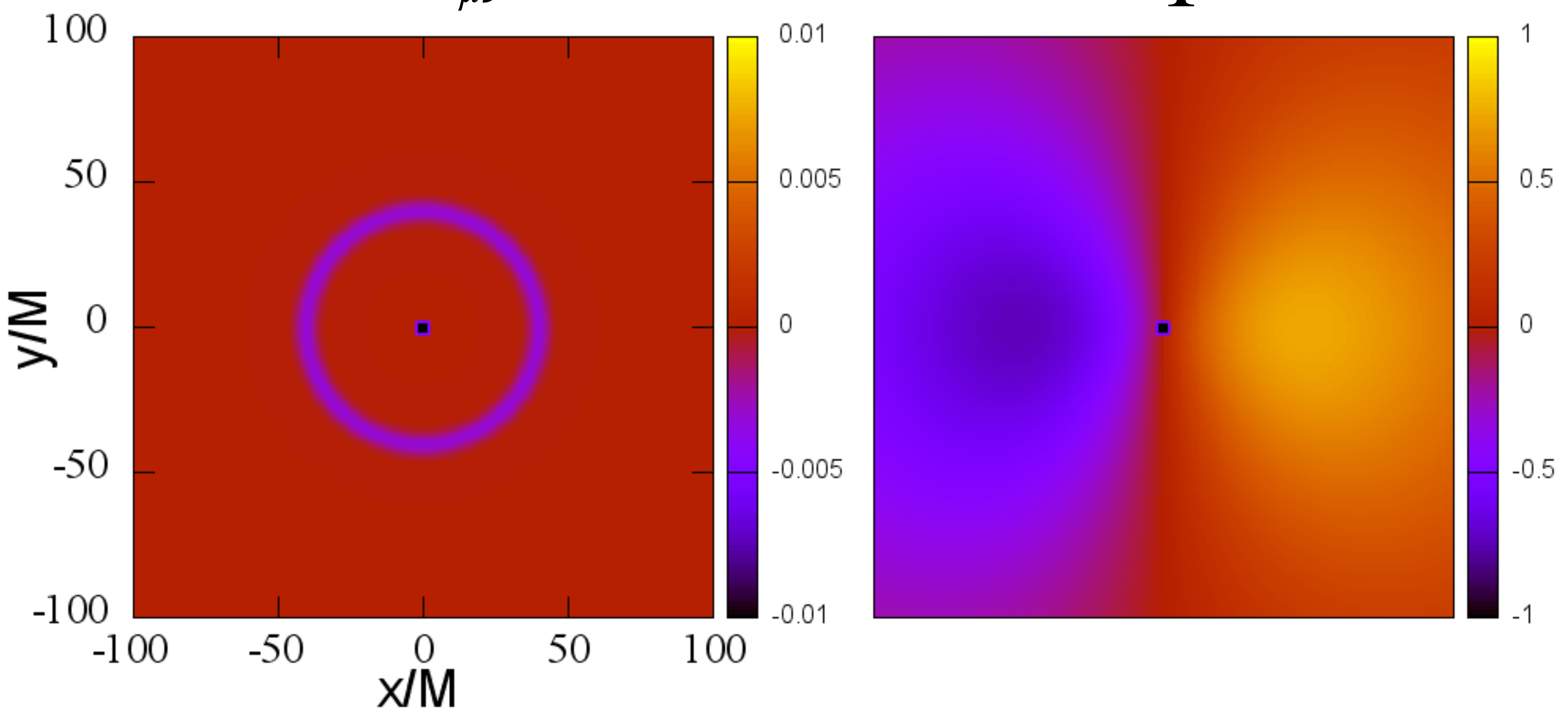
- Dissipation case (Extended initial profile)

$$\begin{cases} (\nabla^2 - \mu^2)\Phi = \dfrac{k_{\mathrm{a}}}{2}\tilde{F}_{\mu\nu}F^{\mu\nu} \\ \nabla_\mu F^{\mu\nu} = 2k_{\mathrm{a}}\tilde{F}_{\nu\mu}\nabla^\mu\Phi \end{cases}$$

$$\mu M = 0.2, \quad k_{\mathrm{a}}A_0 = 0.1$$

t=0.000000 M

$F^{\mu\nu}F_{\mu\nu}$ Φ $z = 0$ plane

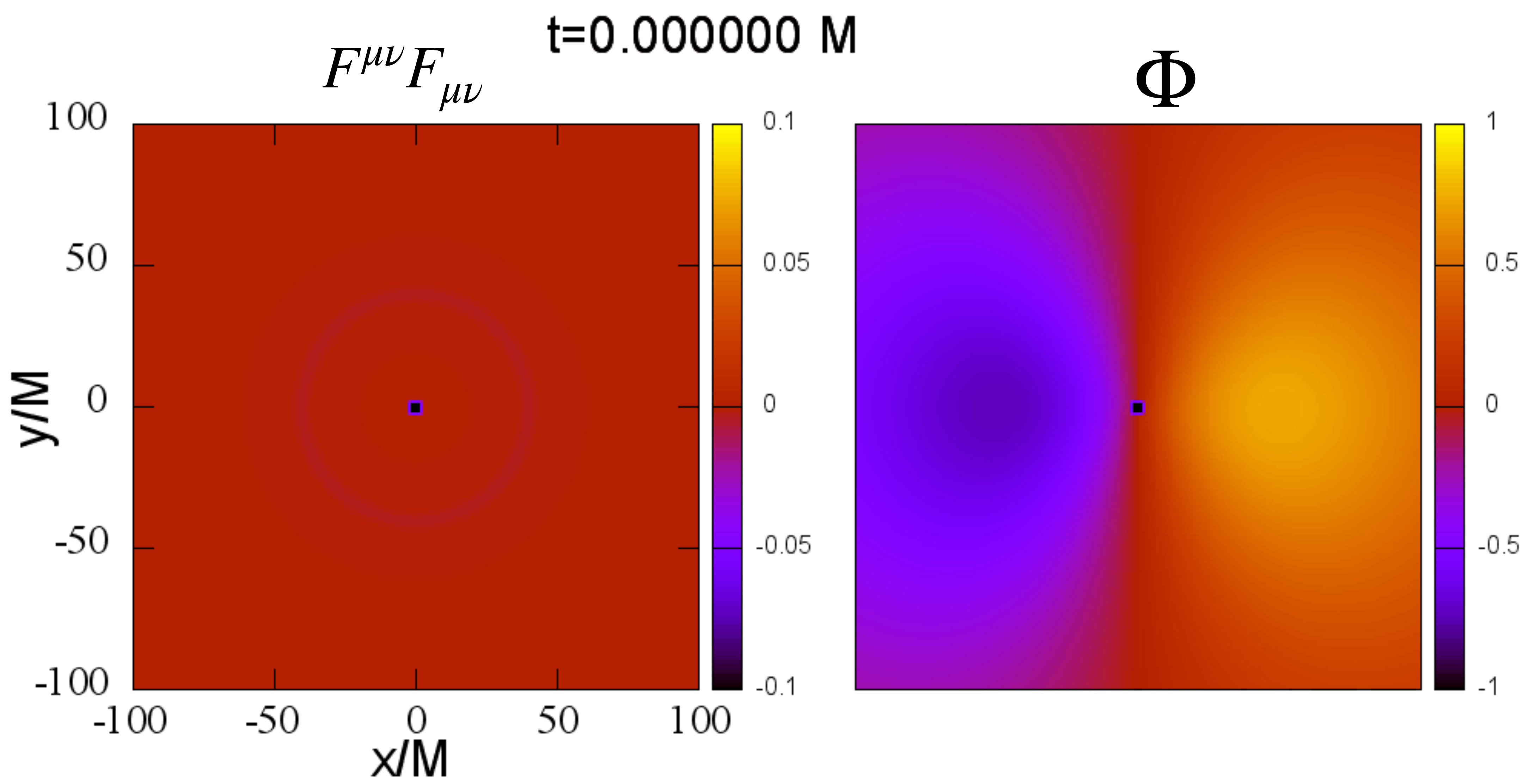


Around Kerr BH

- Burst case (Extended initial profile)

$$\mu M = 0.2, \quad k_a A_0 = 0.3$$

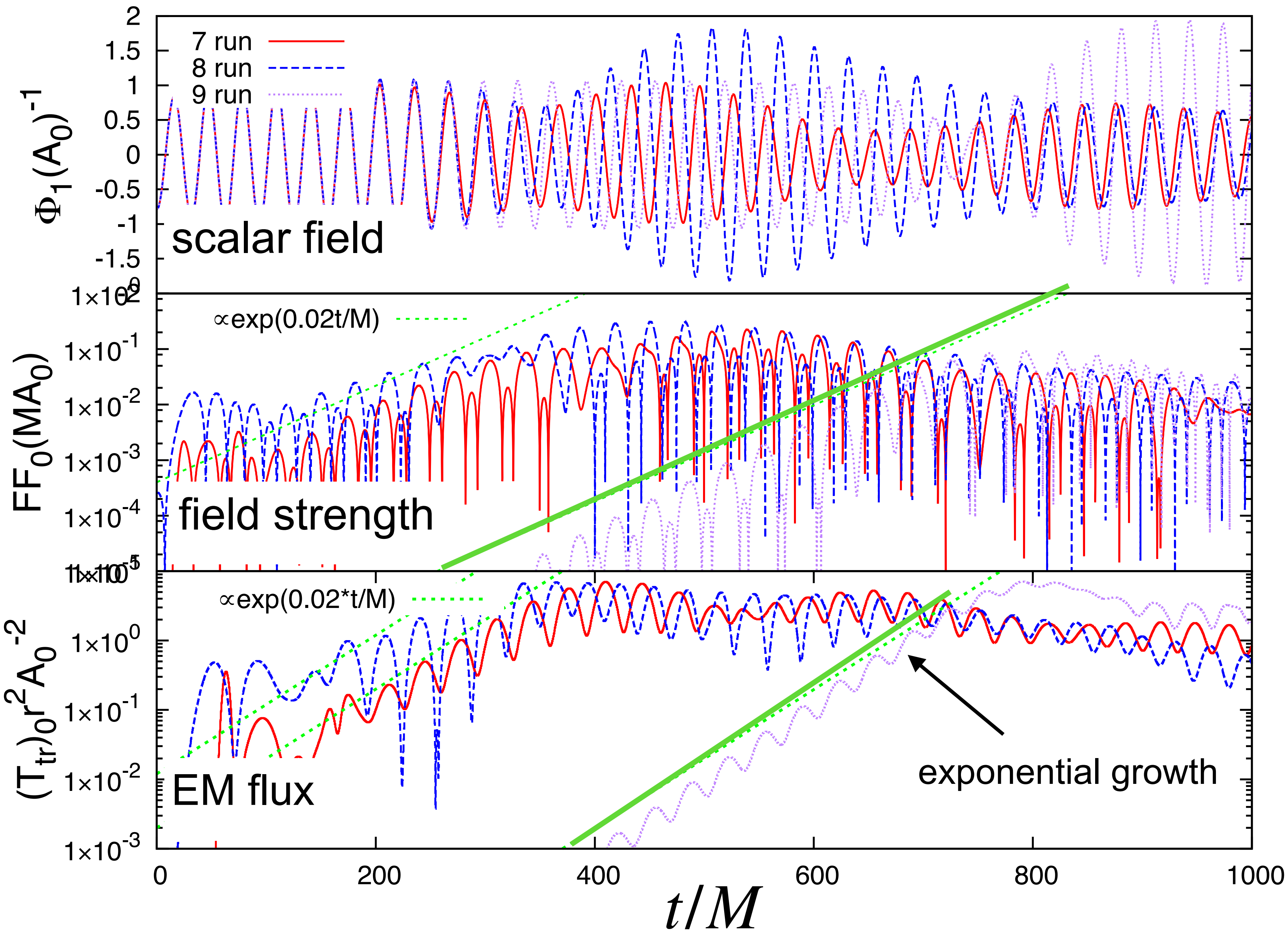
$$\begin{cases} (\nabla^2 - \mu^2)\Phi = \dfrac{k_a}{2}\tilde{F}_{\mu\nu}F^{\mu\nu} \\ \nabla_\mu F^{\mu\nu} = 2k_a \tilde{F}_{\nu\mu}\nabla^\mu \Phi \end{cases}$$



Around Kerr BH

cf: $\Phi_1 = \int d\Omega \Phi \frac{1}{2}(Y_{1,1} + Y_{1,-1})$

- Typical time evolution of the burst



Around Kerr BH

- We could checked
  - the exponential growth for several initial data for $k_{\mathrm{a}} A_0 \geq \text{threshold}$
  - typical frequency of EM field : $\omega = \mu/2$
- Scenario
  - 1.Initial EM pulse dissipates.
  - 2.EM field grows exponentially.
  - 3.Energy of EM field propagates as radiations.
  - 4.Energy of scalar field decrease, and new coupling is below the threshold.
- We get

$$\begin{cases} M & \text{: BH mass} \\ M_{\mathrm{S}} & \text{: total mass of axion cloud} \end{cases}$$

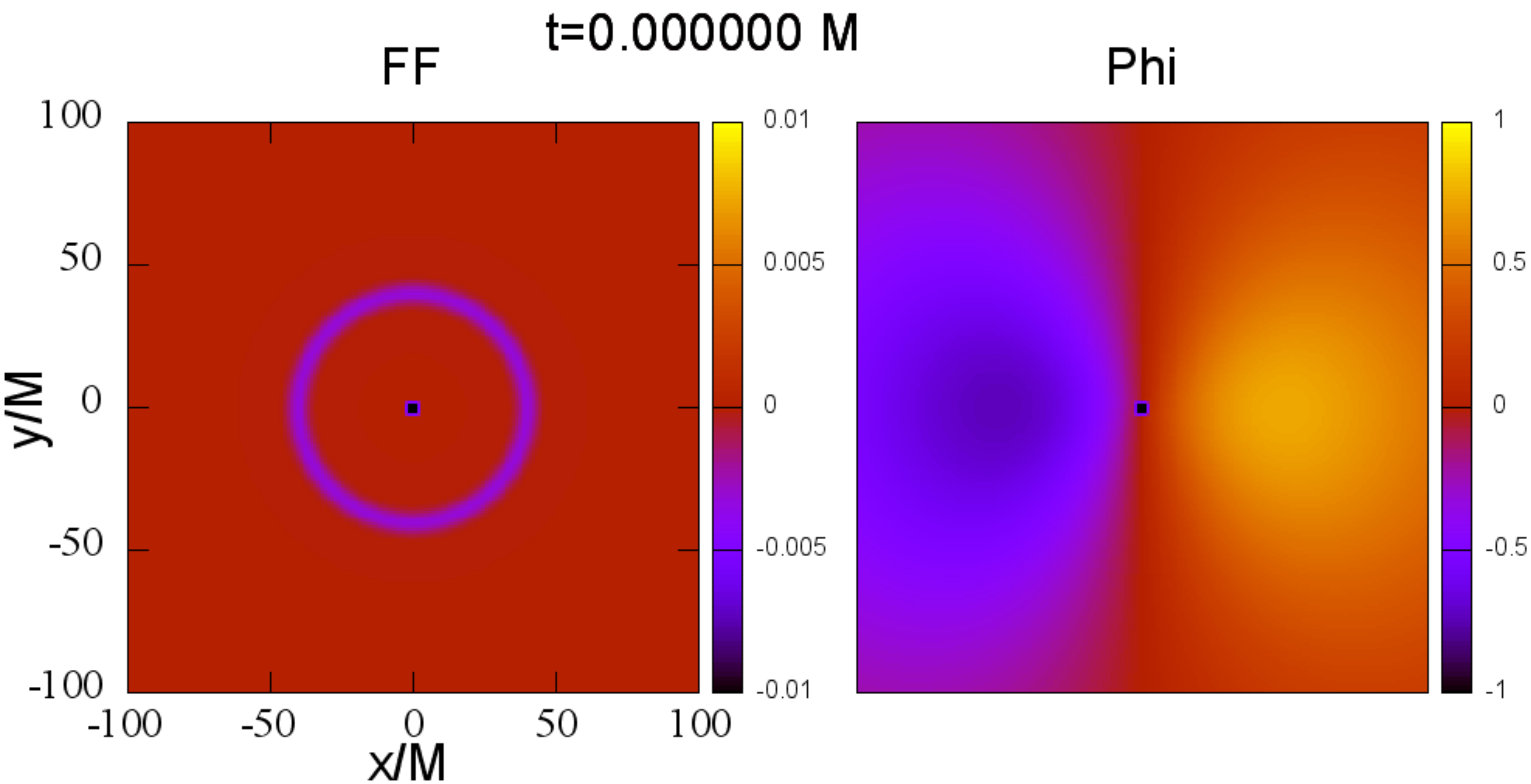
  - luminosity formula: $\frac{dE}{dt} = 5.0 \times 10^{-6} \left(\frac{M_{\mathrm{S}}}{M} \right) \frac{c^5}{G}$
  - threshold for the burst : $\frac{\sqrt{\hbar}}{k_{\mathrm{a}}} < 6 \times 10^{18} \left(\frac{M_{\mathrm{S}}}{M} \right)^{1/2} (\mu M)^2 \ \mathrm{GeV}$

Supper-radiance effect

- The burst is induced by super-radiance effect.
  - We add term to scalar field eq. which induces “super-radiant” like effect.

$$g^{\mu\nu}\nabla_\mu\nabla_\nu\Phi + \underline{C\frac{\partial\Phi}{\partial t}} = \mu^2\Phi + \frac{k_a}{2}\tilde{F}_{\mu\nu}F^{\mu\nu}$$

“super-radiance” time scale $\sim 1/C$



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Summary

- Result
  - Energy of axion cloud transfers to EM field
  - EM field grows exponentially, and burst of EM field occurs.
  - Luminosity of burst

$$\left\{ \begin{array}{ll} M & \text{: BH mass} \\ M_S & \text{: total mass of axion cloud} \end{array} \right.$$

$$\frac{dE}{dt} = 5.0 \times 10^{-6} \left(\frac{M_S}{M} \right) \frac{c^5}{G}$$

  - Threshold for axion couplings

$$\frac{\sqrt{\hbar}}{k_a} < 6 \times 10^{18} \left(\frac{M_S}{M} \right)^{1/2} (\mu M)^2 \text{ GeV}$$

  - The burst is induced by “super-radiance” instability.
  - We also get similar result in the case of scalar type coupling.

cf : $\mathscr{L}_s = -\frac{(k_s \Phi)^p}{4} F^{\mu\nu} F_{\mu\nu} = -\frac{(k_s \Phi)^p}{2} \left(\vec{B}^2 - \vec{E}^2 \right)$

Thank you.